2 ESSENTIAL PLANT NUTRIENTS

2.1. CRITERIA FOR ESSENTIALITY

Plants differ from animals in that they use individual chemical elements and ions as their food. Arnon and Stout (1939) proposed the following criteria for the essentiality of a plant nutrient:

1. A deficiency of the element makes it impossible for a plant to complete its life cycle.
2. The deficiency is specific for the element in question.
3. The element is directly involved in the nutrition of the plant, for example, as a constituent of an essential metabolite or required for the action of an enzyme system.

Based on the above criteria 16 elements are considered as essential for the growth of higher plants. These are carbon (C), hydrogen (H), oxygen (O), nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), iron (Fe), manganese (Mn), copper (Cu), zinc (Zn), molybdenum (Mo), boron (B), and chlorine (Cl).

There is a growing tendency among the plant nutritionists and soil scientists (Mengel and Kirkby, 1987; Tisdale, Nelson, and Beaton, 1985; Nicholas, 1961) to use a less restrictive definition of essentiality of a plant nutrient, for example, avoiding the necessity of establishing symptoms of deficiency and their correction by supplying a specific nutrient. By adapting such a definition, four more elements are added to the 16 elements listed above. These are sodium (Na), silicon (Si), cobalt (Co), and vanadium (V). The essentiality of Na for plants with C_4 photosynthetic pathway has been reported (Brownell, 1968). *Chenopodiaceae* and other plant species adapted to saline conditions take up Na in relatively high amounts (Flower et al., 1977). Crops that require Na for optimum growth include celery, spinach, sugar beet, and turnip (Lehr, 1953). Japanese, Chinese, and Korean researchers (Okuda and Takahashi, 1965; Tanaka and Park, 1966; Lian, 1976; Park, 1976) have established the essenti-

ality of Si for rice. Si addition has also improved the growth of sugarcane (Ayres, 1966; Gascho, 1977). Cobalt is considered essential for microbial fixation of atmospheric nitrogen, namely, rhizobia, free-living nitrogen fixing bacteria, and blue-green algae (Ahmed and Evans, 1960; Johnson et al., 1966). Vanadium has been established as an essential element for some microorganisms (Nicholas, 1961). From the viewpoint of soil fertility management these can be listed as beneficial elements.

Important functions and deficiency symptoms of essential plant nutrients are given in Table 2.1.

Table 2.1 Functions in Plants and Deficiency Symptoms of Plant Nutrients

Nutrient (forms absorbed)	Functions in plants	Deficiency symptoms
	Primary nutrients	
Nitrogen (NH_4^+, NO_3^-)	Synthesis of amino acids, proteins, chlorophyll, nucleic acids, coenzymes	Light-green colored leaves, lower leaves turn yellow and die in severe deficiency
Phosphorus ($H_2PO_4^-$, HPO_4^-)	Metabolic transfer processes, ATP, ADP, photosynthesis, and respiration; component of phospholipids	Purplish leaves, especially on the margins
Potassium (K^+)	Involved in sugar and starch formation; lipid metabolism and nitrogen fixation; neutralizes organic acids	Marginal burning of leaves, curling of leaves
	Secondary nutrients	
Calcium (Ca^{2+})	Component of cell walls; cell growth and cell division; cofactor for some enzymes	Failure in the development of terminal bud, dead spots in the mid rib of some plants. In corn, tip of the new leaves may be covered with a sticky, gelantinous material that causes them to adhere to one another

Table 2.1 Functions in Plants and Deficiency Symptoms of Plant Nutrients (Continued)

Nutrient (forms absorbed)	Functions in plants	Deficiency symptoms
Magnesium (Mg^{2+})	Component of chlorophyll, hence essential for food synthesis in plant	Light green leaves and yellowing of leaves similar to N. In rapeseed the leaves are cupped inward
	Micro-nutrients	
Zinc (Zn^{2+})	Formation of auxins and chloroplasts; carbohydrate metabolism; stabilizing and structural orientation of membrane proteins	Stunted growth, pale to white coloration of young leaves — white bud and white streaks in leaves of corn; brownish red (rusty) discoloration of leaves in rice known popularly as “Khaira” disease in rice. Corn, beans, citrus, and rice are indicator plants for zinc deficiency
Manganese (Mn^{2+})	Photosynthesis-evolution of oxygen, oxidation-reduction processes, decarboxylation and hydrolysis reactions	Intervenous discoloration — green veins against a pale background; whitening and abscission of leaves, gray speck of oats, marsh spots of peas
Iron (Fe^{2+})	Structural component of cytochromes, perrichrome, and leghemoglobin and thus involved in oxidation — reduction reactions in respiration and photosynthesis	Yellowing or whitening of young leaves. In severe deficiency in rice nurseries, or direct-seeded rice or sorghum fields the entire plants may turn pale or white. Pale yellow interveinal chlorosis in stem
Copper (Cu^{2+})	Constituent of chlorophyll, catalyst for respiration, carbohydrate, and protein metabolism	Stunted growth, terminal leaf buds die, leaf tips become white, and leaves are narrowed and twisted

Table 2.1 Functions in Plants and Deficiency Symptoms of Plant Nutrients (Continued)

Nutrient (forms absorbed)	Functions in plants	Deficiency symptoms
Boron (BO_3^-)	Involved in germination and pollen tube growth; fruiting, cell division, nitrogen metabolism	Terminal buds die, rosette formation, flower or fruit shedding
Molybdenum (MoO_4^-)	Essential component of nitrate reductase and nitrogenase, thus important in N fixation by legumes	Resembles N-deficiency symptom, whip tail disease of cauliflower
Chlorine (Cl^-)	Involved in the evolution of oxygen in photosystem II of photosynthesis, raising cell osmotic pressure	Chlorotic leaves, some leaf necrosis

From Grundon et al. (1987); Katyal and Randhawa (1983); Mengel and Kirkby (1987); Tisdale et al. (1985); Tanka and Yoshida (1970).

2.2. BASIS FOR CLASSIFICATION OF NUTRIENTS AS PRIMARY, SECONDARY, AND MICRONUTRIENTS

Of the 16 essential nutrients, C, H, and O are taken from the air and soil water, while the other 13 are supplied by the soil, and hence the study of their amounts, forms in which they are present, and reactions that they undergo individually or with each other form the core of soil fertility and its management.

2.3. PRIMARY NUTRIENTS, SECONDARY NUTRIENTS, AND MICRONUTRIENTS

On the basis of the amounts in which these 13 elements are taken up by the crop plants, they are classified as follows.

Primary nutrients (N, P, and K). These nutrients are taken up by the crop plants in the largest amount (Table 2.2) and are the nutrients most commonly applied almost each crop season unless organic farming is practiced. Production of materials containing one or more of these three nutrients is the goal of the World Fertilizer Industry, and the materials are known as fertilizers. Some fertilizers do contain some secondary and micronutrients also.

Secondary nutrients (Ca, Mg, and S). These nutrients are taken up in the next largest amounts (Table 2.2), next only to N and K, but uptake is

Table 2.2 Nutrient Uptake by Spring Wheat[a]

Primary Nutrients	kg ha^{-1} [b]	kg Mg^{-1} grain[c]
N	128	28.0
P	20	4.4
K	187	41.0
Secondary nutrients		
Ca	27	5.9
Mg	19	4.2
S	22	4.9
Micronutrients	**g ha^{-1}**	**g Mg^{-1} grain**
Fe	1800	400
Zn	500	100
Mn	500	100
Cu	150	30

[a]Wheat received 120 kg N ha^{-1} and yielded 4.6 t ha^{-1} grain and 6.9 t ha^{-1} straw; samples not analyzed for B, Mo, and Cl.

[b]Total for grain and straw.

[c]Obtained by dividing total (grain + straw) uptake by the grain yield.

From Joshep and Prasad. 1992. Fert. News 37(3): 33–35. With permission.

generally equal to or greater than P. Consequently, a point is being raised whether Ca, Mg, and S should be considered secondary nutrients or should be promoted as primary nutrients. Since most soils having a pH of 7.0 or above have abundant Ca and even Mg, these nutrients are generally not required to be added to crops each season. Some fertilizers marketed to supply the primary nutrients such as ammonium sulfate, ammonium sulfate nitrate, and ordinary superphosphate also contain large amounts of S. However, with the advent of high-analysis fertilizers such as anhydrous ammonia (83% N), urea (46% N), and diammonium phosphate (18% N and 46% P_2O_5), S deficiency is showing in several parts of the world and S is now considered the fourth most important fertilizer nutrient after N, P, and K.

Micronutrients (Fe, Mn, Zn, Cu, B, Mo, and Cl). These nutrients are taken up by the plants in very small amounts, generally reported in g ha^{-1} as compared with kg ha^{-1} in the case of primary and secondary nutrients. On deficient soils these nutrients have to be applied either to the soil or to the crop plants as a foliar spray. Micronutrients are also termed trace elements. Average concentrations of micronutrients in plants and their uptake relative to that for Mo, as estimated by Epstein (1972), are given in Table 2.3.

Table 2.3 Average Concentrations of Micronutrients in Plants

Micronutrient	Proportion according to dry weight: mol g^{-1}	Proportion according to dry weight: mg kg^{-1}	Relative number of atoms compared with Mo
Mo	0.001	0.1	1
Cu	0.10	6.0	100
Zn	0.30	20	300
Mn	1.0	50	1000
B	2.0	20	2000
Fe	2.0	100	2000
Cl	3.0	100	3000

From Epstein. 1972. *Mineral Nutrition of Plants — Principles and Perspectives*, p. 63. With permission of John Wiley & Sons, New York.

2.4. FUNCTIONS OF ESSENTIAL NUTRIENTS IN PLANTS

Irrespective of the class to which they belong, all essential nutrients are equally important from the viewpoint of plant growth. For better crop production these elements need to be present in adequate amounts of available forms in soil(s). They must also be positionally available; that is, concentrations must be adequate within the soil volume in which the crop roots are active. Plant nutrient concentrations may be inadequate, insufficient, deficient, toxic, or excessive. By definition, when plant growth is satisfactory and optimum yields can be obtained, the amounts are adequate. However, if optimum yields cannot be reached because of nutrient deficiencies, the amounts are said to be insufficient. At nearly adequate levels of nutrient supply, deficiency symptoms are often difficult to detect visually. When a plant nutrient is present in amounts significantly lower than adequate levels, the deficiency symptoms in plants are then expressed and the nutrient is said to be deficient. When the amount of a plant nutrient is present in excess of the plant's needs, it may reach the level at which it causes the deficiency of other nutrients or results in environmental pollution. At such levels the nutrient is present in excessive amounts. When concentration of an essential nutrient or any other element is too high, it may become toxic to the plant. For example, under lowland conditions iron and manganese toxicities are often reported. Whether an element is abundant, insufficient, deficient, excessive, or toxic depends upon crop, soil, and soil-plant ecosystem. Critical deficiency and toxicity contents of various elements in the rice plant are given in Table 2.4. The margin between critical deficiency and toxicity limits is quite narrow for trace elements, especially Cu, B, and Fe. Soil fertility management for sustainable agriculture aims at maintaining essential plant nutrients in adequate amounts and includes plans for taking care of insufficiencies, deficiencies, excesses, or toxicities of essential plant nutrients.

Table 2.4 Critical Deficiency and Toxicity Contents of Various Elements in the Rice Plant

Element	Deficiency (D) or toxicity (T)	Critical content	Plant part analyzed	Growth stage[a]
N	D	2.5%	leaf blade	T
P	D	0.1%	leaf blade	T
P	T	1.0%	straw	M
K	D	1.0%	straw	M
K	D	1.0%	leaf blade	T
Ca	D	0.15%	straw	M
Mg	D	0.10%	straw	M
S	D	0.10%	straw	M
Si	D	5.0%	straw	M
Fe	D	70 ppm	leaf blade	T
Fe	T	300 ppm	leaf blade	T
Zn	D	10 ppm	shoot	T
Zn	T	1500 ppm	straw	M
Mn	D	20 ppm	shoot	T
Mn	T	2500 ppm	shoot	T
B	D	3.4 ppm	straw	M
B	T	100 ppm	straw	M
Cu	D	<6 ppm	straw	M
Cu	T	30 ppm	straw	M
Al	T	300 ppm	shoot	T

[a]*M*, maturity; *T*, tillering.

From Tanaka and Yoshida. 1970. *Nutritional Disorders of Rice Plant*, p. 150. With permission of International Rice Research Institute, Manila, Philippines.

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